



High Strength, Dissimilar Alloy Aluminum Tailor-Welded Blanks

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June 7, 2017

Project ID #LM099

Project Overview

Project Timeline

- ▶ Start: FY2015
- ▶ Finish: FY2017
- ▶ 80% complete

Budget

- ▶ Total project funding
 - DOE – \$1.2 M
 - Industrial cost share >\$1.2M
- ▶ FY15 Funding - \$400k (received)
- ▶ FY16 Funding - \$400k (received)
- ▶ FY17 Funding - \$400k (received)

Technology Gaps/Barriers

- ▶ High volume, high-yield joining technologies for lightweight and dissimilar materials needs further improvement. (VT Multi-Year Program Plan 2.5.1F)
- ▶ Scientific understanding to enable joining of work-hardenable and precipitation hardenable alloys is lacking.
- ▶ Scientific understanding of joining in curvilinear geometries in dissimilar thickness and alloy combinations is lacking.

Partners

- ▶ Automotive OEM
 - ▶ General Motors
- ▶ Tier I Supplier
 - ▶ TWB Company LLC
- ▶ Material Provider
 - ▶ Arconic
- ▶ Project Lead
 - ▶ PNNL



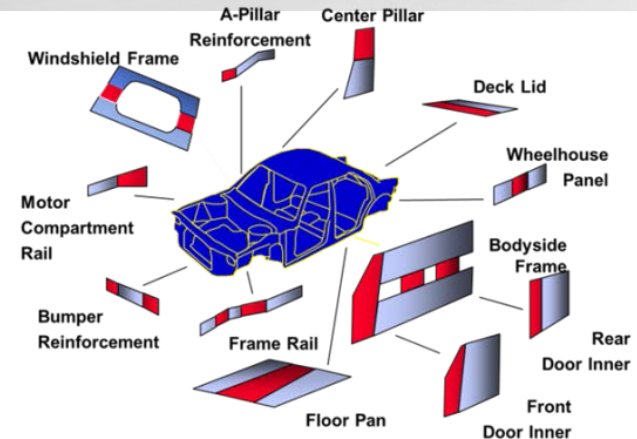
Relevance: Project Motivation

- ▶ VTO - Challenges and Barriers:
 - “Joining thin sheets or sheets with different thicknesses is difficult...new joining and forming technologies...will need to be developed.”
 - Joining method must be rapid, affordable, repeatable, and reliable.
 - Material supply chain and production industry needs to expand
- ▶ Project is designed to address each of these issues
 - Develop high speed, low cost, robust joining technique
 - Develop a supplier base
 - Develop and validate predictive modeling tool

EERE-VTO Goal:

By 2025, demonstrate a cost-effective 35% weight reduction in passenger-vehicles compared to 2010 model (<\$4.8/ Kg saved)

Cost modeling by supplier showed weight savings at \$3.74 /kg with the use of AL- TWB.
 (VTO goal<\$4.8/ Kg)



Front Door Inner Example	Steel –TB 1.4 / .7 mm	Al – Assembly	AL – TB 2.0 / 1.1 mm
Gross Weight	14.5 kg	9.0 kg	7.4 kg
Net Weight	11.6 kg	6.8 kg	6.6 kg
Material cost (\$1.25/kg vs \$4.50/kg)	\$18.13	\$40.50	\$33.30
Blanking & Welding	\$3.12	\$.70	\$5.85
Stamping	\$2.00	\$3.60	\$2.80
Assembly	\$0	\$3.00	\$0
Total Cost	\$23.25	\$47.80	\$41.95
Net Weight Savings*	n/a	4.8 kg	5.0 kg
Cost / kg saved**	n/a	\$5.11	\$3.74

*Actual weight saving per panel is less when door assembly is considered

**Costs / kg saved is lowered with the use of TWB vs. assembly

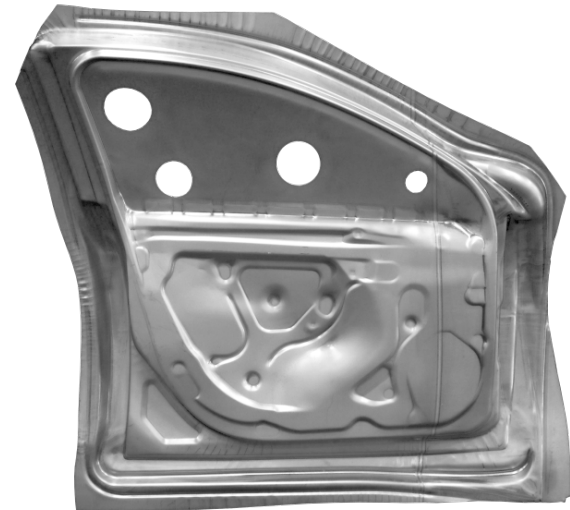
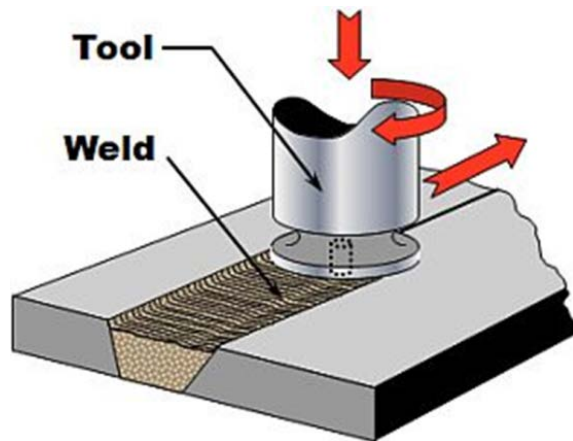
Relevance: Project Objectives

► Overall Objectives:

- Develop joining technology needed for high speed fabrication of high strength, dissimilar alloy Al-TWBs in linear and curvilinear geometries.
- **Hand off the matured technology to industry.**



► Objective (FY 2016-FY2017)

- Demonstrate high-speed, dissimilar alloy friction-stir welding between 5xxx, 6xxx and 7xxx alloys.
- Complete repeatability and deployability study at suppliers facility.
- Validate formability model for dissimilar alloy and thickness.



Project Milestones



Month/Year	Milestone or Go/No-Go Decision
Sept 2016 Go/No-Go Complete 	Demonstrate high-speed, dissimilar alloy friction stir welding between 5x & 6x alloys in linear and curvilinear geometries.
April 2017 Progress Milestone 	Demonstrate high-speed, friction-stir welded dissimilar alloy welded blanks between 5x & 6x alloys to 7x alloys
June 2017 Progress Milestone	Validate formability model for dissimilar alloy and thickness.

Approach: Project Schedule and Progress

✓ FY16 Go/No-Go →

✓ FY17 Milestone →

✓ FY16 Milestone →

FY17 Milestone
On track →

	FY2015				FY2016				FY2017			
Quarter	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1: Relating weld parameters and material properties												
1.1. Sheet Characterization												
1.2. FSW properties												
1.3. HAZ relationships												
1.4. Effects of Coatings												
1.5. Dissimilar Joint Properties												
Task 2: Dissimilar Alloy FSW Development												
2.1. 5xxx to 6xxx												
Decision Gate:												
2.2. 6xxx to 6xxx												
2.3. 5xxx & 6xxx to 7xxx												
2.4. Curvilinear weld development												
Task 3: Production readiness and deployability												
3.1. Repeatability - Linear												
3.2. Repeatability - curvilinear												
3.3. Durability - tools												
Task 4: Weld formability modeling and validation												
4.1. Barlat Coefficients												
4.2. Dissimilar Thickness												
4.3. Dissimilar alloy & thickness												
4.4. Prototypical validation												

▶ **Task 1: Relating Weld Parameters & Material Properties**

- Task 1.1. Base-metal sheet characterization
- Task 1.2. FSW material characterization
- Task 1.3. Heat affected zone characterization and analysis
- Task 1.4. Effects of sheet coatings on properties of weld
- Task 1.5. FSW characterization & properties of dissimilar alloy joints

▶ **Task 2: Dissimilar Alloy Friction Stir Welding Development**

- Task 2.1. Dissimilar alloy weld development of 5xxx and 6xxx
 - **Decision gate**
- Task 2.3. Dissimilar alloy weld development of 5xxx and 6xxx alloys to 7xxx
- Task 2.4. Curvilinear high speed FSW development

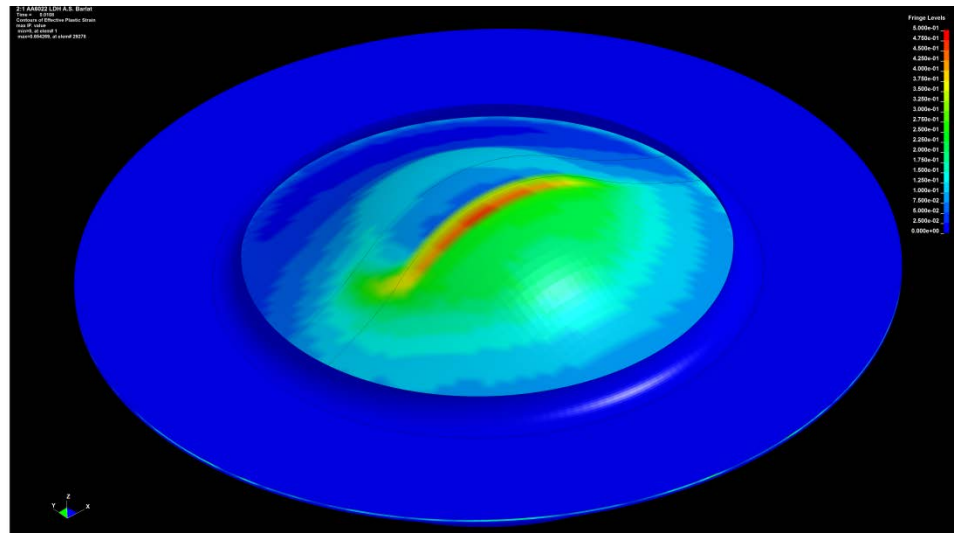


► **Task 3: Production Readiness and Deployability**

- Task 3.1. Repeatability of high speed dissimilar alloy FSW
- Task 3.2. Repeatability of high speed curvilinear FSW
- Task 3.3. Tool durability

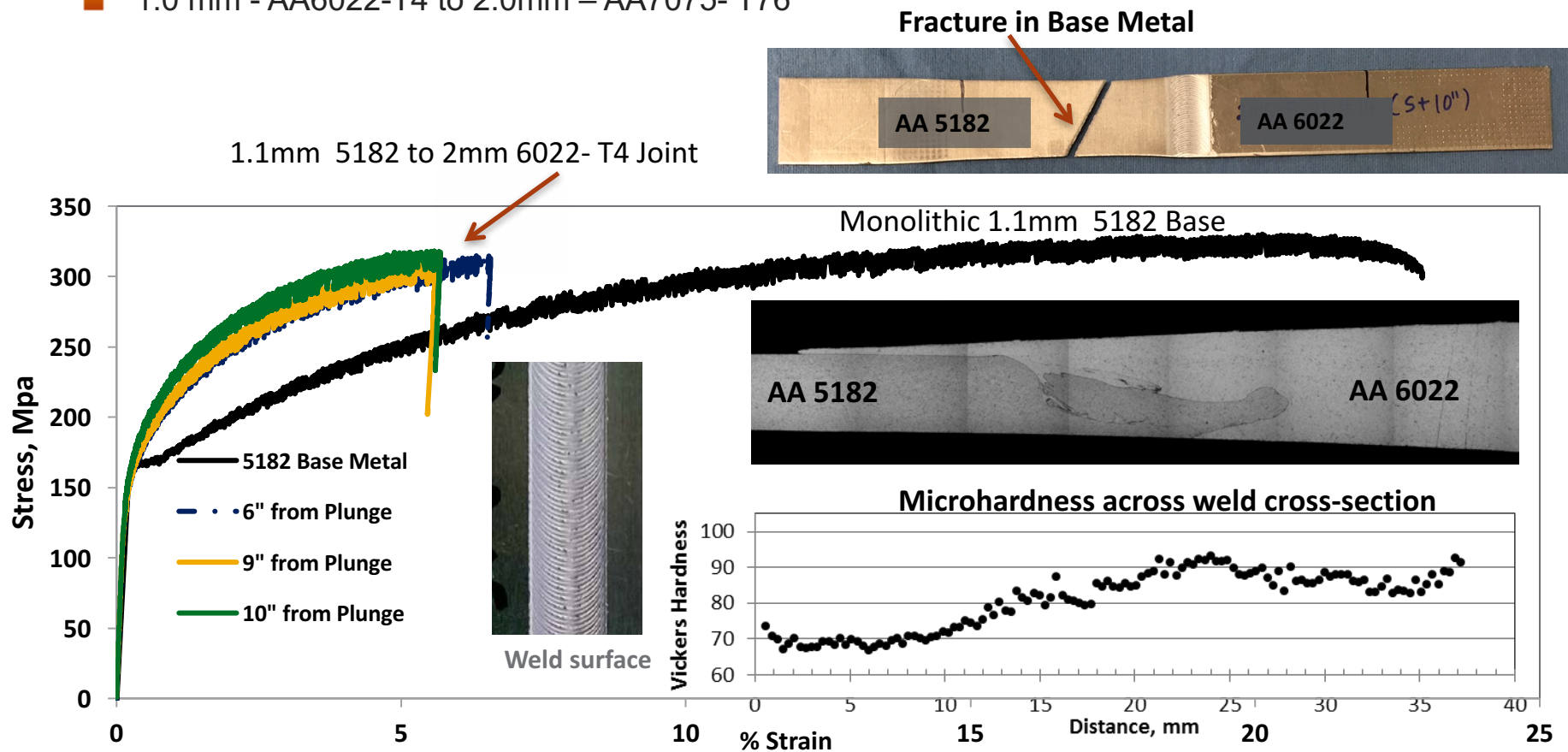
► **Task 4: Weld Formability Modeling and Validation**

- Task 4.1. Developing Barlat Coefficients
- Task 4.2. Simulating formability of dissimilar thickness Al TWBs
- Task 4.3. Simulating formability of dissimilar alloy & thickness Al TWBs



Task 2 - Dissimilar Alloy FSW Development (FY 16 Go-No-Go)

- ▶ We have developed process parameters for effective joining of work hardenable and precipitation strengthened alloys (Demonstrated welding speeds 2.5-4.5m/min)
 - 1.1 mm - AA5182-O to 2.0 mm - AA6022-T4
 - 1.1 mm - AA5182-O to 2.0 mm – AA7075- T76 and AA7085- T76 (FY 17 Milestone)
 - 1.0 mm - AA6022-T4 to 2.0mm – AA7075- T76

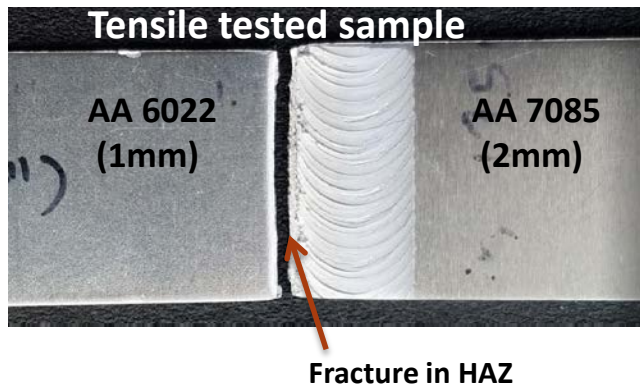


Technical Accomplishments:

Task 2 - Dissimilar FSW Development: Age Hardening alloys

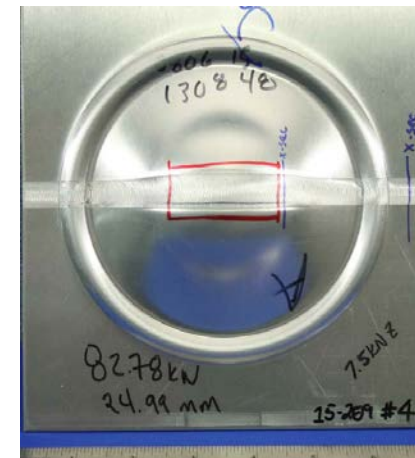
High volume production

- ▶ High volume production demands immediate ability to evaluate weld quality. If welds have to sit for 96 hours prior to testing (age hardenable alloys), thousands of parts would have been completed prior to evaluation.
- ▶ PNNL worked with TWB to develop test criteria in as welded condition.
- ▶ Test result in as welded state was a good indicator of joint performance in naturally aged state. Joints that passed the test in as welded condition also passed after natural aging.



Test Criteria

Bend test (Root side, Face side)
LHD test (Root side , Face side)
Tensile test.



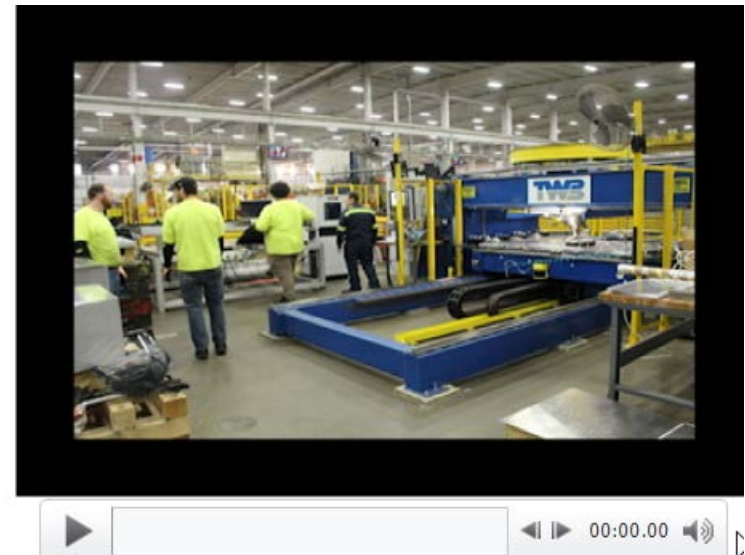
Face side LDH with HAZ fracture

Technical Accomplishments:

Task 3 - Repeatability- for production readiness

Linear welds

- ▶ 1000+ linear welds were run over several days
 - Simulates the number of welds produced in a single automated shift
- ▶ Dissimilar thickness sheet (with 0.8mm differential) were welded.

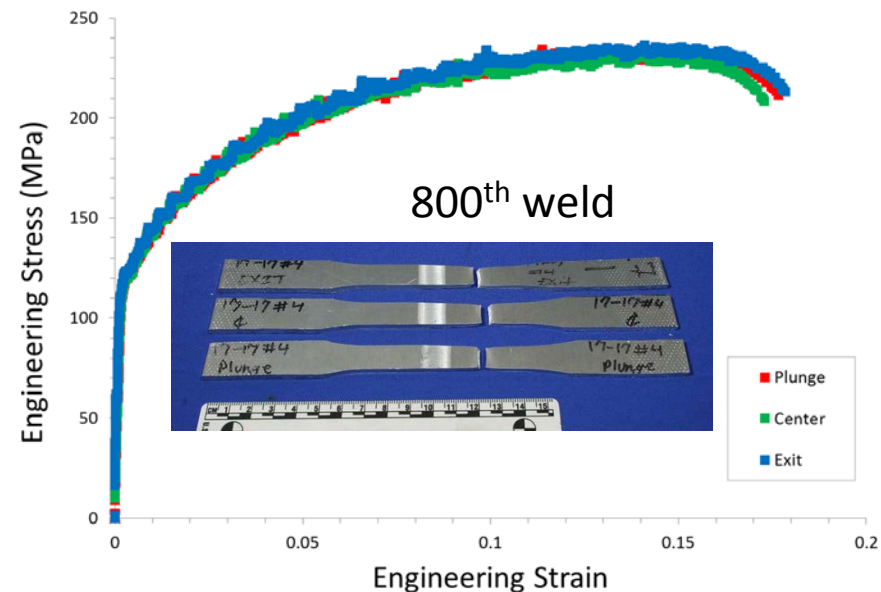
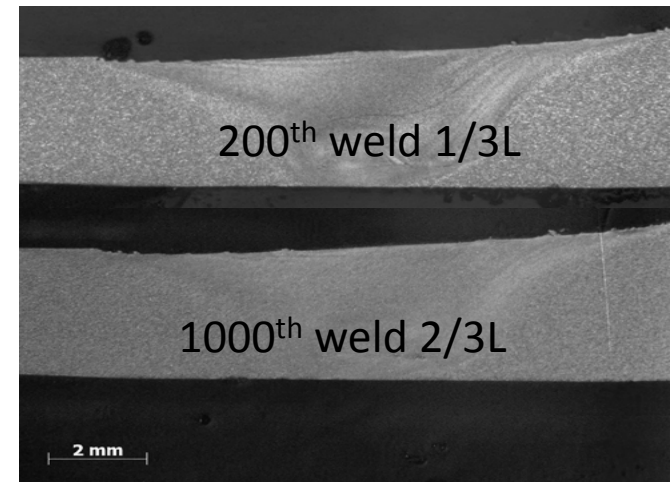
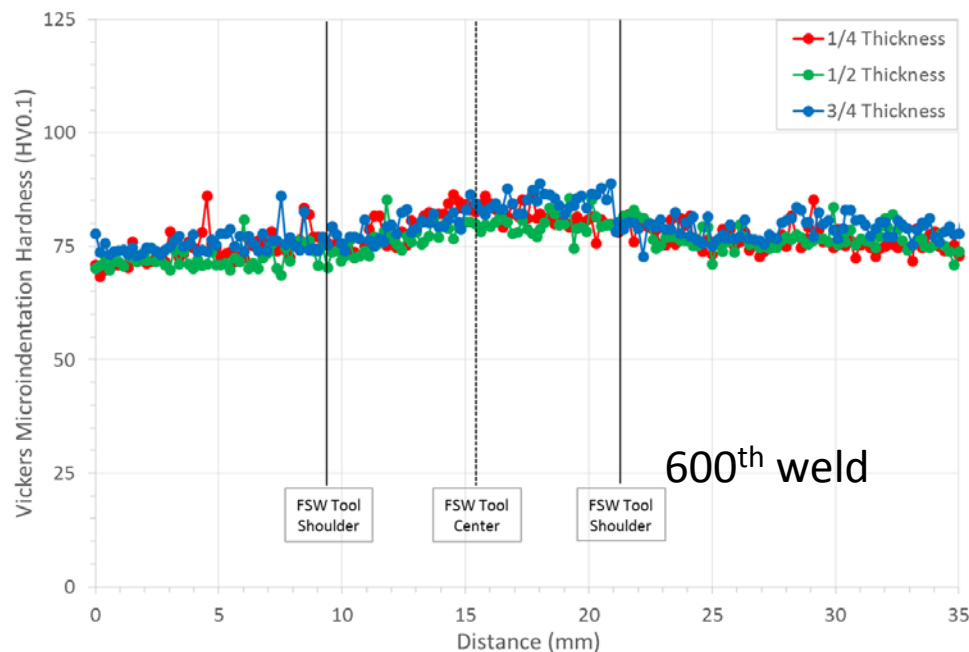


Technical Accomplishments:

Task 3 - Repeatability- for production readiness

Linear welds (contd.)

- ▶ Completed repeatability study on linear welds
- ▶ Observed consistent properties from start to finish
 - Characterizations including micro-hardness, ASTM E-8 tensile tests and optical cross-sections were performed on every 200th weld at beginning, middle and end of weld panel.
 - UTS: 234.3 MPa \pm 2.7
 - Elongation: 17.1% \pm 1.0



Technical Accomplishments

Task 3: Tool Durability

- ▶ Tool durability tests was performed to simulate FSW tools performing for a full shift
- ▶ Two tools were used for the durability study (yellow and purple)
 - Yellow tool welded ~300 meters, purple tool welded ~500 meters
- ▶ No measurable wear on tools after 500 meters of welding (>600 welds)

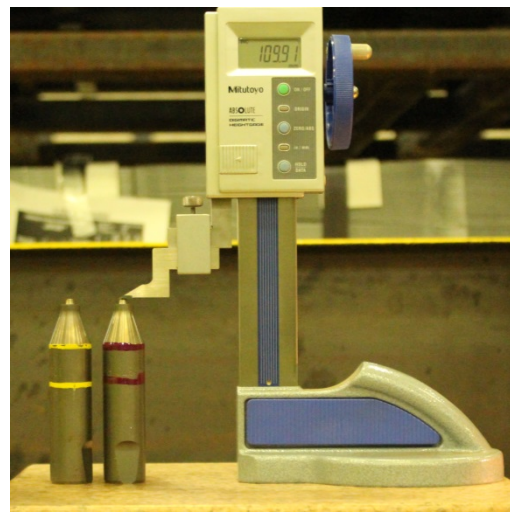
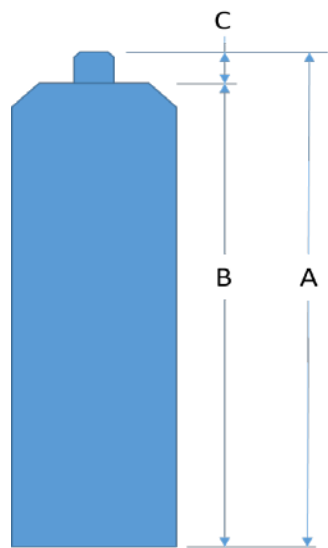


Measurements (New)

A	B	C
109.91	106.73	3.18
109.91	106.72	3.18

Measurements (Final)

A	B	C
109.91	106.72	3.18
109.91	106.72	3.18

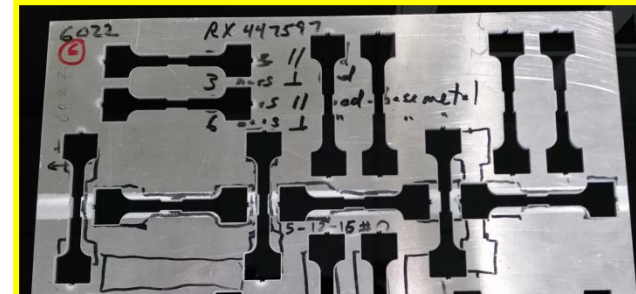


Technical Accomplishments:

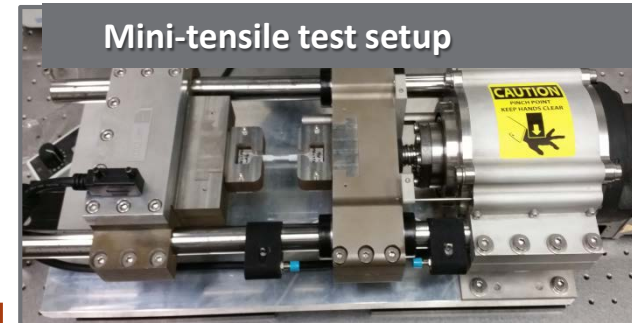
Task 4.1 Barlat coefficients for welded material

- ▶ Mini-tensile and bulge tests were conducted on base material and welded regions (6022 and 5182)
 - Tensile tests were done along RD, TD, DD
 - Bulge test conducted to account for equi-biaxial behavior
 - Mini-samples were cut from base material and weld in 3 directions (RD, TD, and DD (45 degree))
 - Samples were speckle patterned and DIC used for strain measurement
- ▶ Barlat anisotropy parameters were evaluated for both alloys in the base metal and the weld.

Mini Tensile samples cut outs



Mini-tensile test setup

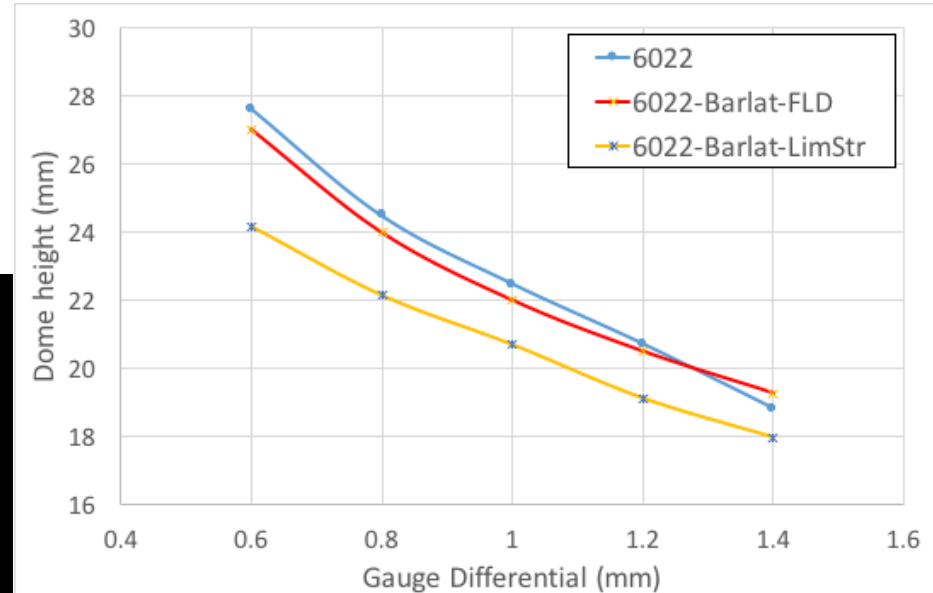
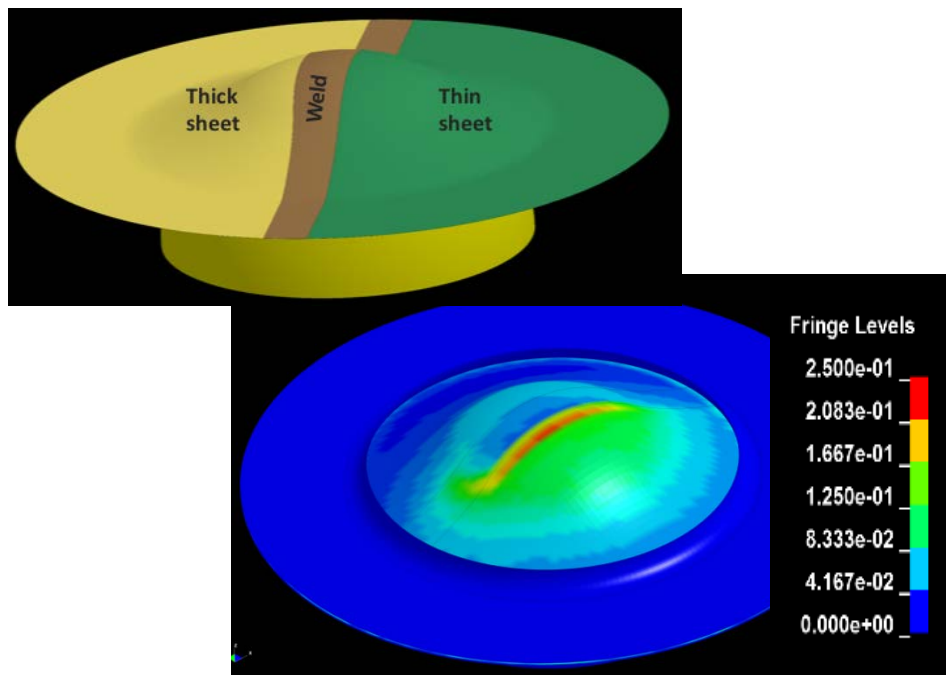


Barlat Parameters for 6022

	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8
6022 base	0.9817	0.9982	0.8472	1.0480	1.0134	1.0187	0.9178	1.2110
6022 weld	0.9826	1.0499	1.0254	1.0170	1.0132	1.0688	1.0118	0.97

Technical Accomplishments:

Task 4.1, 4.2 Implementation of Barlat coefficients for welded material



- ▶ Barlat model accounts for material anisotropy.
- ▶ Sheet was discretized using different material anisotropy properties (Barlat coefficients) for the base metal and the weld.
- ▶ Simulations were conducted for dissimilar thicknesses and alloys Al TWB.
- ▶ Predicted dome heights were determined for 2 'failure' criteria:
 - Using FLD data
 - Using limiting strain from tensile data

Responses to Previous Year Comments

- ▶ Reviewer: *“this project appears to be highly focused, well organized, and is on track to achieve its goals. A key thing is that the project has engaged the entire supply chain, right thought to an eventual technology deployment client.”*
 - The team agrees that the success of the project is dependent on active involvement of partners from different aspects of supply chain with individual goals.
- ▶ Reviewer: *“would like to see actual stamping trials in the last phase to show performance of the FSW blanks under truly high strain rate forming, and taking it beyond limiting dome height (LDH) testing.”*
 - Full size parts made using FSW during has been successfully stamped. Prototypical part from dissimilar thickness/ dissimilar alloy joint will be stamped as a part of model validation task.

Collaboration and Coordination

▶ University Collaborators

■ Washington State University

- Tasked with characterization of TWB joints

▶ Industrial Collaborations (complete automotive supply chain)

■ General Motors

- Lead in determining Barlat coefficients for weld material, product specific formability modeling, component stamping

■ TWB Company, LLC.

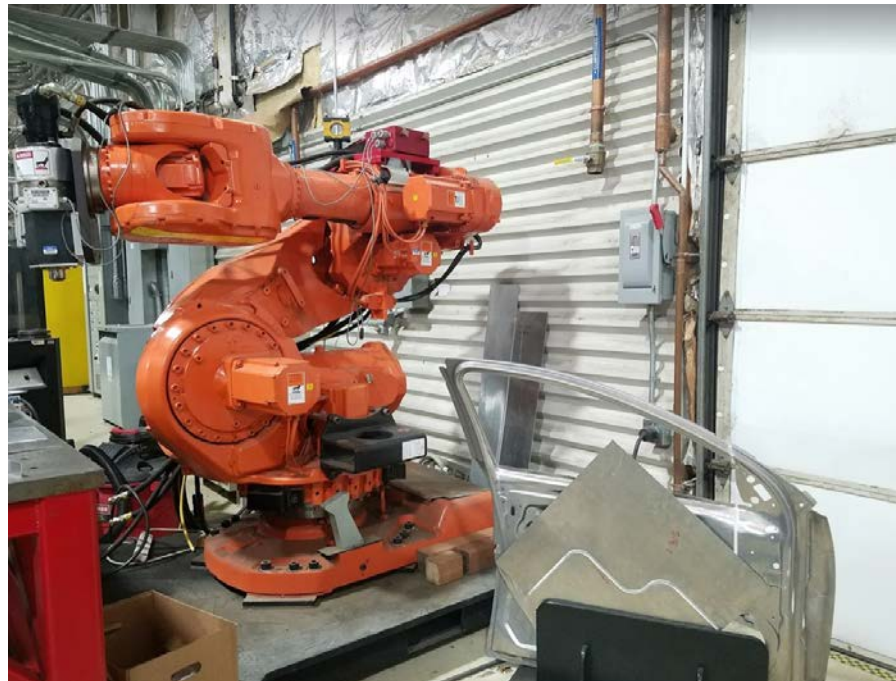
- High speed linear and curvilinear blank production, repeatability evaluations, tool durability testing during high volume production

■ Arconic

- Material provider.

Remaining Challenges and Barriers

- ▶ Effects of sheet “coatings” on properties of weld
 - Task 1.4 : completing the study at TWB facility
- ▶ Production Readiness of dissimilar alloy blanks in curvilinear paths
 - Task 3: addressing repeatability of curvilinear joints
- ▶ Predictive engineering tools need expand to include dissimilar alloys
 - Task 4.3 Demonstrate formability model for dissimilar alloy combinations
 - Task 4.4 Validate final model on a prototypical part.



Proposed Future Work (planned)

- ▶ Complete assessment of effects of coatings on FSW of TWB (TWB Inc.)
- ▶ Demonstrate process repeatability for dissimilar material, dissimilar thickness in curvilinear paths. (TWB Inc. and PNNL)
- ▶ Complete predictive modeling tools for dissimilar alloy TWBs using Barlat coefficients developed for the base material, weld material, etc. (FY17 milestone) (GM, PNNL)
- ▶ Complete validation of the predictive model. (GM, PNNL)

Any proposed future work is subject to change based on funding levels.

Summary of Accomplishments

- ▶ High speed friction stir welding of 4.5m/min has been developed to join dissimilar aluminum alloys in dissimilar thickness.
- ▶ We have successfully transferred welding parameters developed at laboratory scale to suppliers facility resulting in industry capability to effectively join AA5182 to both AA6022 and AA7075 in dissimilar thickness.
- ▶ We have demonstrated production readiness of high speed linear FSW by performing process repeatability and tool wear/durability study.
- ▶ We have integrated Barlat 2000 coefficients of FSW weld region into predictive modeling tool.

Summary of Future tasks

- ▶ Repeatability of FSW process in joining dissimilar alloys/ dissimilar thickness in curvilinear paths will be completed.
- ▶ Formability model will be expanded to include dissimilar alloy joints.
- ▶ Formability model will be validated on a prototypical part.



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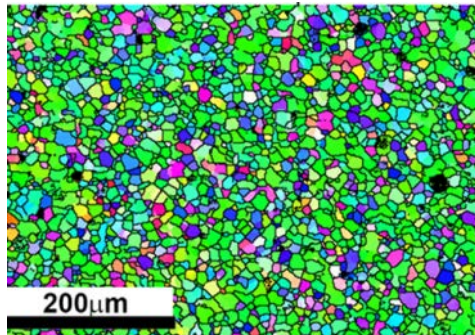
Technical Back-Up Slides

Weld microstructure

1m/min @ 1500 RPM

$T_{\max} = 470^{\circ}\text{C}$

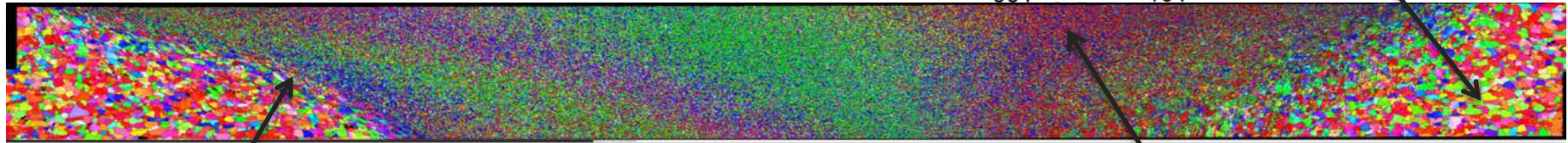
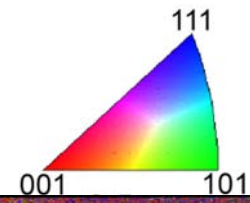
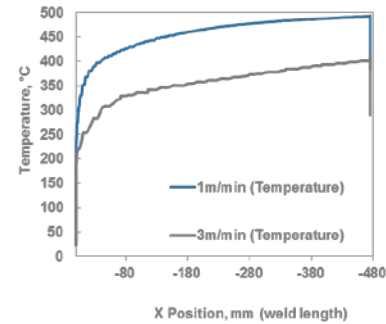
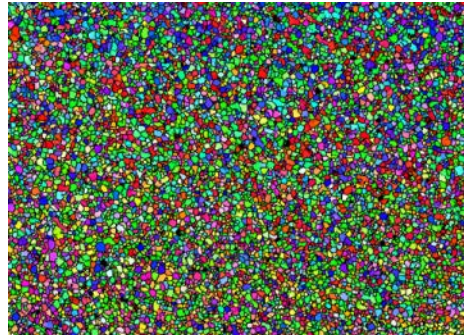
Average Grain Size: $8.7\ \mu\text{m}$,
Grain size variance: $27\ \mu\text{m}$



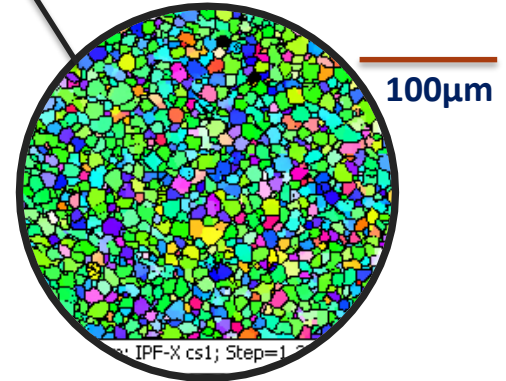
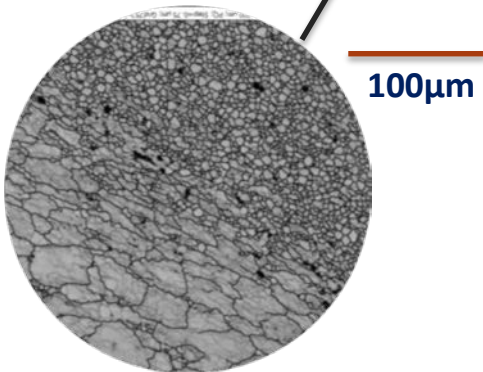
3m/min @ 1500 RPM

$T_{\max} = 355^{\circ}\text{C}$

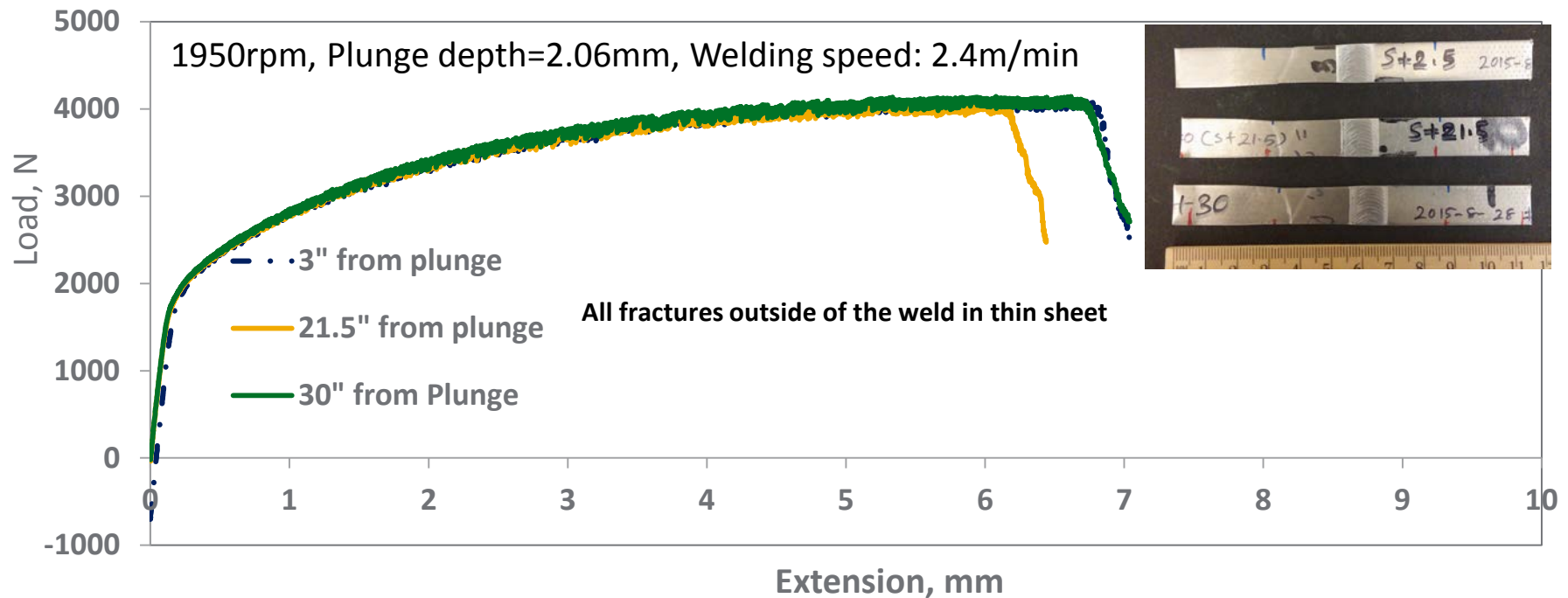
Average Grain Size: $5.6\ \mu\text{m}$,
Grain size variance: $8.3\ \mu\text{m}$



3m/min, 1950rpm, AA 6022 joint.



Joint tensile test results for : AA7075- AA 5182

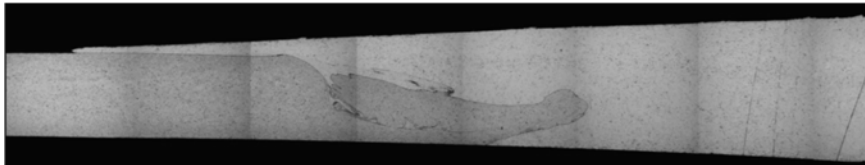


Dissimilar weld properties

6022- 5182



As polished Cross-section

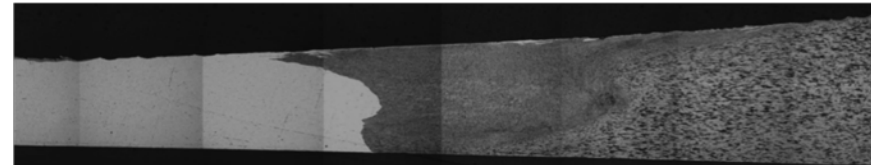


Etched Cross-section

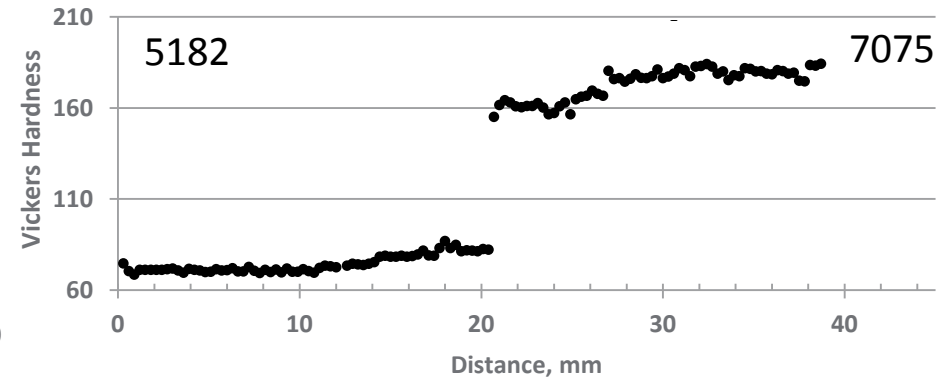
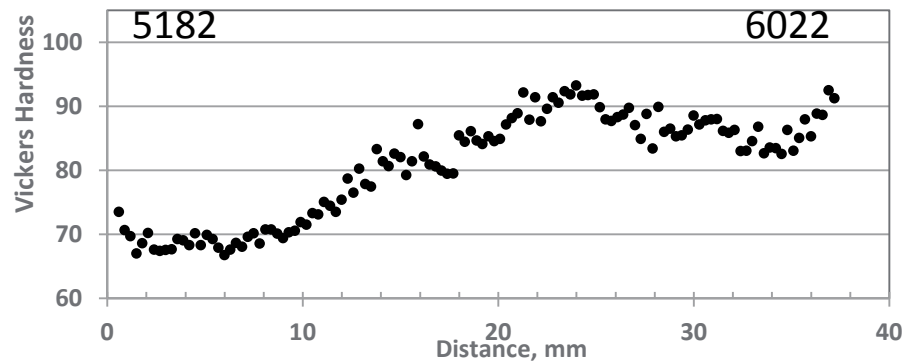
7075- 5182



As polished Cross-section



Etched Cross-section



- ▶ Joint cross-sections and hardness data illustrates mixing of dissimilar materials within the nugget.

Technical Accomplishments: Curvilinear weld path in dissimilar material set.



- ▶ Welding parameters for curvilinear weld path for dissimilar alloys and thickness have been developed for corners with 50 and 60mm radiuses.
- ▶ Successful demonstration of transferring linear high speed friction stir welding to a fully curvilinear geometry.

Barlat (2000)* Yield Function

- ▶ Yield function to describe anisotropy during large deformation of sheet metal
- ▶ Yield function coefficients are obtained using experimental data collected from a few tests: (i) three uniaxial tension tests in different orientations (0, 45, 90), and (ii) one balanced biaxial bulge test.

*Barlat et al. International Journal of Plasticity 19 (2003) 1297–1319

